The Use of Magnetic Signatures in Identifying Shallow Intrusions on the Moon. P. A. Jackson[1], L. Wilson[1,2] and J.W. Head[2], [1]Environmental Science Division, Institute of Environmental and Biological Sciences, Lancaster University, Lancaster LA1 4YQ, U.K., [2]Department of Geological Sciences, Brown University, Providence, RI 02912, U.S.A.

Abstract: Some lunar graben (linear and arcuate rilles) may form as a result of shallow dyke intrusion, since the significantly negative buoyancy of lunar basalts in the anorthositic crust means that many dykes stall before reaching the surface [1]. Because the Moon exhibits remanent magnetism, shallow dykes are also a potential source of magnetic anomalies near the lunar surface [2]. Using a trace from the Apollo 15 sub-satellite showing magnetic field variations between (19S, 68W) and (2N, 44E) [3], all the graben near the satellite ground track were analysed using the methods of Head & Wilson [1] to determine the likelihood that they were formed by shallow intrusions. Three strong candidates were found among the thirteen examined, and others are possible.

Analysis: Mastin & Pollard [3] showed how the stress induced by a shallow intrusion would affect surface deformation and fracturing to produce graben. Head & Wilson [1] applied this analysis to two lunar graben, using the widths and depths of the graben to infer the depths to the dyke tops and the mean widths of the dykes. We used their Fig. 2b (after noting a typographic error in the strain labels) to carry out the same analysis for an additional eleven graben near the Apollo 15 sub-satellite ground track. By assuming that the horizontal extent of the outcrop of a dyke is comparable to the vertical extent of the dyke [4], a minimum source depth for the magma in the inferred dyke can be estimated from the observed graben length. For a dyke originating from the base of the crust (depth of 64 to 100 km) to stall near the surface, a driving pressure in the range 14 to 20 MPa is needed which corresponds to a dyke width of 150 to 200 m, and if the dyke originated from a strength trap in the mantle (depth or order 300 km) it would need a driving pressure of ~50 MPa, corresponding to a dyke width of 600 to 800 m [5]. Using these limits it is possible to determine if a given graben could plausibly have been formed by shallow dyke intrusion.

Results: The results of the analyses of the graben near the magnetic trace are shown in the Table below. Three strong candidates for formation due to shallow dyke intrusion are apparent, Rimae Sirsalis, Parry V and Hyginus. All three have associated volcanic features, and their inferred dyke widths and source depths are compatible with the necessary conditions. Two other possible candidates are the rilles in Alphonsus (also linked to volcanic activity) and the rille cutting the rim of Hipparchus. These and the other graben are now discussed in turn.

Rima Sirsalis has an implied minimum magma source depth of 300 km and an implied dyke width of 600 m. Thus it is possible that Rima Sirsalis formed due to a shallow intrusion of magma originating at a strength trap in the mantle.

Rima Parry V has an implied minimum source depth of 50 km and an implied dyke width of ~150 m. Thus it is plausible that Rima Parry V formed above a dyke originating at the base of the crust.

Rima Hyginus has a minimum source depth of 120 km and an implied dyke width of ~250 m. Thus it is plausible that Rima Hyginus formed due to shallow intrusion of a dyke originating just below the base of the crust.

The graben studied in Alphonsus has a minimum source depth of 25 km and an implied dyke width of.100 m, and thus appears too small to be due to shallow dyke intrusion. However, the volcanic features in Alphonsus are likely to have been fed by dykes propagated from magma intruding the brecciated zone beneath Alphonsus in association with the flooding of Mare Nubium [6], giving an effective source depth of order 20 km, consistent with our measurement.

The graben studied in Hipparchus has a minimum source depth of 37 km and an implied dyke width of.~175 m. Since the source depth is deduced from the graben length and this may not fully reflect the dyke length if the upper edge is significantly curved, this dyke too is a marginal candidate for shallow intrusion.

Rima Ariadaeus is probably a radial graben generated in response to basin formation. The inferred source depth and dyke width are too large for a dyke propagating from the base of the crust and probably too small for a dyke propagating from a strength trap in the mantle.

The other arcuate graben investigated are all thought to have been formed tectonically in response to basin formation and loading of the maria. The likelihood that some could be the result of shallow dyke intrusion, with the resulting graben being curved due to the nature of the stress fields in crustal rocks at the edges of basins, is small, as the inferred source depths and dyke widths are not consistent with the expected behaviour of dykes

The dykes that fed the mare flood basalts must still be present in the crust;.when surface eruption ceased the surface fissure vent may have closed due to stress relaxation and been buried by lava drainback; but the shape of the dike required to deliver negatively buoyant magma to the surface will have been such as to leave a cooling crustal dyke of enormous volume [5]. Further investigation of magnetic data should help identify some of these dykes and hence locate vent sites for mare eruptions.

If the magnetic signatures in the trace we studied are indeed the result of shallow dyke intrusion, then the distance of the dike from the trace (and the dyke size) will affect the magnetic field flux ratio. We therefore plotted the flux ratio for each peak on the trace against [(distance from trace)/(graben length)], i.e. D/L in the Table for the graben associated with that peak. As this ratio increases the flux ratio would be expected to decrease, though various factors such as the orientation of the dyke, might greatly complicate the correlation.

The predicted trend of decreasing flux ratio with increasing D/L is apparent in the graph (not shown here), especially at low D/L where most of the data points are for the graben inferred to have been formed by shallow dyke intrusion. All of the points with D/L greater than ~5, which form a separate trend on the graph, are from arcuate or radial tectonic graben (which tend to have small values of L). However, there are two "tectonic" graben with very low values of D/L, the radial Rima Ariadaeus and an arcuate rille, and these must be assumed to lie by chance on the expected trend for intrusions. With some care, therefore, the flux ratio-(D/L) plot may be used to help identify graben formed by dyke intrusion. There is one major anomaly on the flux-(D/L) graph: the graben in Alphonsus with a D/L of 10 and a flux ratio of 0.38. The high flux ratio in this case is probably the result of complications from ignoring the several other graben with volcanic associations on the floor of Alphonsus.

Conclusion: Our analysis finds at least 4 probable examples of shallow intrusions with remanent magnetic signatures on the Moon and suggests that use of magnetic data can greatly enhance other methods of identifying the presence of shallow dykes.

References: [1] Head, J.W & Wilson, L. (1993) PSS 41, 719. [2] Srnka, L et al. (1979) Phys. Earth. Plan. Int. 20, 281. [3] Mastin, L.G. & Pollard, D.D. (1988) JGR 93, 13221. [4] Takeda, A (1990) JGR 95, 8471. [5] Head, J.W & Wilson, L. (1992) GCA 56, 2155. [6] Wilson, L. & Head, J.W. (1979) Proc. LPSC 10, 2861.

Table: Lat, Long of flux measurement and Flux value; Orbiter frame and feature name; Type (R = radial, C = concentric, Cr = partly in crater, V = associated volcanics); L = graben length, equal to minimum magma source depth; D = distance of graben from trace; G = graben width; T = inferred depth to dyke top; W = inferred dyke width.

Lat/Long	Flux	LO Frame	Rille Name	Type	L (km)	D (km)	G (m)	T (m)	W (m)	D/L
-15, -61	0.95	IV162H	Rima Sirsalis	R, V	300	0	3720	1200	413-534	0.0
-11, -29	0.22	IV132H	25S, 28W	C	19	450	2480	940	367-552	23.7
-11, -29	0.22	IV143H	R. Mersenius III	C	15	100	3810	1490	374-422	6.7
-11, -29	0.22	IV125H	25S, 25W	C	252	600	2880	1100	189-258	2.4
-10, -17	0.38	V38M	Rima Parry V	Cr, V	50	75	1840	680	93-171	1.5
-9, -9	0.38	IV108H	in Alphonsus	Cr, V	25	250	640	220	43-160	10.0
-7, 4	0.25	IV101H	in Hipparchus	Cr	37	60	790	280	106-343	1.6
-8, 8	0.22	III73M	Rima Hyginus	V	120	400	2010	750	194-346	3.3
-5, 14	0.15	IV90H	Rima Ariadaeus	R	165	350	3800	1490	326-367	2.1
-3, 22	0.22	IV84H	Rima Hypatia I	C	12	90	3190	1230	118-150	7.5
-2, 36	0.18	IV73H	Rima Cauchy I	C	16	400	2830	1080	142-196	25.0
-1, 38	0.25	IV73H	Rima Cauchy I	C	16	400	2830	1080	142-196	25.0
0, 44	0.17	IV65H	Fossa Messier	M	10	350	500	170	59-260	35.0